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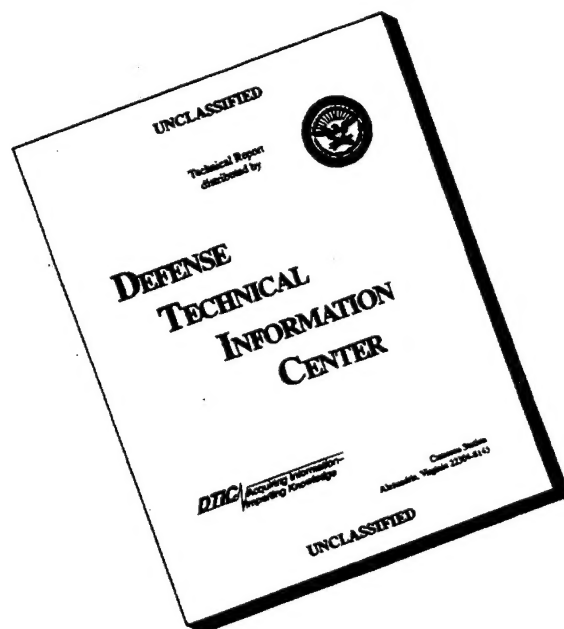
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WAPD-T-268

Properties of Zircaloy-2

D. E. Thomas and F. Forscher

Abstract

Work on the mechanical and corrosion properties of Zircaloy-2 is reviewed. The strength and ductility properties are given as a function of testing temperature, heat treatment, and cold work. The role of hydrogen in affecting ductility is mentioned. The corrosion behavior of Zircaloy-2 as influenced by composition, heat treatment, and impurity content is presented. The pickup of hydrogen during corrosion is discussed in terms of corrosion mechanism. Implications of corrosion data in terms of heat transfer characteristics are pointed out.

PROPERTIES OF ZIRCALOY-2INTRODUCTION

The rapid development of reactor technology within the past five to ten years with its needs for new materials presents a challenge to the metallurgist, chemist and materials engineer. Among the materials used in reactors is the "new" metal zirconium and its alloys which are attractive from the point of view of their low neutron absorption. This desirable characteristic of zirconium is offset by its low strength properties and its highly variable corrosion behavior in the commercially pure condition. Zircaloy-2, a low alloy of zirconium, was developed by the Westinghouse Atomic Power Division during 1952. Its desirable properties are consistently good corrosion resistance in high temperature water, improved strength properties for design, sufficient ductility for fabrication and little change in neutron absorption due to the alloy additions. Nominally, Zircaloy-2 is a sponge-zirconium-base alloy containing 1.5 w/o tin, 0.12 w/o iron, 0.05 w/o nickel and 0.10 w/o chromium. The use of Zircaloy-2 has increased in proportion to the development of water cooled reactors. The purpose of this paper is to acquaint reactor technologists with concise and up to date information on the properties of this alloy. The information is subdivided into three sections. (A) Composition and Physical Properties (B) Mechanical Properties and (C) Corrosion Behavior.

A. COMPOSITION AND PHYSICAL PROPERTIESComposition

A typical composition range according to specification PDS 11538-4 for Zircaloy-2 (strip, bar or forging) is given below in weight percent.

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Tin	1.3-1.6
Iron	0.07-0.20
Chromium	0.05-0.16
Nickel	0.03-0.08
Average (Fe + Cr + Ni)	0.23-0.32
Nitrogen, Max.	0.006

The impurity content does not exceed the following limits in parts per million (ppm)

Aluminum	50	Magnesium	20
Boron	0.5	Manganese	50
Cadmium	0.5	Molybdenum	50
Carbon	500	Silicon	100
Cobalt	10	Titanium	50
Copper	50	Tungsten	50
Hafnium	200	Vanadium	50
Lead	100		

The limits on nitrogen content are included in the composition range because of its importance to corrosion resistance. No limit has been set on the hydrogen content although its detrimental effect on ductility is known. The commonly encountered hydrogen content is about 40 to 50 ppm. The oxygen content varies between 1400 and 2500 ppm with a mean value of about 1800 ppm. The source of the oxygen is usually the sponge-zirconium base material which is always higher in oxygen than is crystal bar zirconium. The major contribution of the oxygen content is its strengthening effect at ambient temperatures but this effect decreases with increasing temperatures.

Physical Properties

The physical properties of Zircaloy-2 are listed in the following table.<sup>1/</sup>

Density:  $6.55 \text{ gm/cm}^3 = 0.237 \text{ lb/in}^3$  (at room temperature)  
Thermal Expansivity:  $6.5 (10)^{-6}/^{\circ}\text{C}$  (from room temperature to  $350^{\circ}\text{C}$ )  
Modulus of Elasticity:  $14.0 (10)^6 \text{ psi}$  ( $dE/dT = -5500 \text{ psi}/^{\circ}\text{F}$ )  
Poisson's Ratio: 0.31

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Thermal Conductivity:

25°C	8.41 BTU/hr/ft/°F
100°C	8.12 "
400°C	8.19 "

Transformation Temperatures and Process Temperatures<sup>1/</sup>

Material initially in the hot rolled condition does not recrystallize completely in a time of 30 minutes until a temperature of 800 to 850°C is reached. Annealing in the alpha range for any reasonable time does not produce grain growth. The laboratory annealing treatment is 750°C for 20 hrs in vacuum and furnace cool.

Dilatometer curves exhibit features due to a eutectoid reaction probably involving iron, nickel and chromium, and due to the alpha to beta transformation of zirconium as affected by the tin and oxygen content. On heating at a rate of 100°C/hr the reaction due to the presence of iron, nickel and chromium begins at approximately 830°C and transformation to beta begins at about 900°C. On cooling the reverse reactions end at 780 and 870°C, respectively.

B. MECHANICAL PROPERTIES

The interpretation of most forming processes in terms of strength and ductility data obtained from tensile tests is, at best, a complex undertaking. Therefore, many other mechanical tests have been designed to simulate the expected forming operation or the expected service condition. For the purpose of this discussion, however, tensile strength and hardness on the one hand and tensile ductility and impact data on the other hand will be used to evaluate the effect of variables such as test temperature, heat treatment, cold work, and directionality on the strength and ductility of Zircaloy-2.

DISCUSSION OF STRENGTH PROPERTIES

Tensile and Yield Strengths

The tensile strength in the longitudinal direction decreases with increasing temperature as shown in Fig. 1. For comparison purposes the

strength-temperature curve for arc-melted crystal bar zirconium is also shown. The square symbols represent the average of two tests in the hot rolled (as-received) condition.<sup>2/</sup> In order to evaluate the variability of the material, tensile specimens from ten ingots were tested and the standard deviation calculated.<sup>3/</sup> The results are given below in Table I and the distribution at room temperature is sketched in Fig. 1. Tensile specimens taken transverse to the rolling direction differ little in strength from their longitudinal counterpart at all temperatures, but the data show a larger variability.

Table I  
Average Mechanical Properties of Zircaloy-2<sup>3/</sup>  
(1 specimen per condition per ingot from 10 ingots)

Room Temperature		260°C	
Long.	Trans.	Long.	Trans.
Mean value ± Standard Deviation			

As-received\*

0.2% Y.S. (1000 psi)	49.4 ± 5.5	70.0 ± 4.8	24.4 ± 2.5	34.1 ± 6.5
Tensile Str. (1000 psi)	75.6 ± 3.2	77.5 ± 5.1	41.5 ± 2.2	41.8 ± 5.0
Red. in Area (%)	28.3 ± 5.2	37.1 ± 6.3	42.2 ± 8.2	52.4 ± 3.8

Base-annealed \*\*

0.2% Y.S. (1000 psi)	44.5 ± 1.8	67.8 ± 2.3	---	---
Tensile Str. (1000 psi)	74.8 ± 1.7	74.0 ± 1.6	---	---
Red. in Area (%)	28.4 ± 2.6	40.0 ± 3.4	---	---

The thermal history of as-received material is:

\* (1) Forging at 980°C with an 80% reduction, (2) rolling at 845°C with a reduction of 97% (3) 5% cold reduction and (4) annealing at 845°C (1550°F) for 10 minutes.

\*\* 750°C for 20 hours in vacuum and furnace cooled

The effect of cold work on the strength properties is shown in Fig. 1 by the curve passing through the open circle symbols. The curve shows the increase in tensile strength at all temperatures caused by 60% cold rolling. This is close to the practical limit of cold working for Zircaloy-2; further cold rolling produces pronounced edge cracking and often results in failure during rolling. It is perhaps surprising that strength properties in the longitudinal and transverse direction do not differ by more than a few thousand psi even after 60% cold rolling.

The yield strength (0.2% offset) of Zircaloy-2 parallels the behavior of the tensile strength with respect to the effects of temperature, annealing and cold work. Typical values are shown in Table I.

Annealing decreases the strength properties at all temperatures as shown by the triangular symbols in Fig. 1. Annealing was done at 750°C for 20 hours in vacuum.

A typical metallurgical structure subsequent to the annealing treatment is shown in Fig. 2a and 2b. The stringer-like formation, which appears on longitudinal sections only, is also present in the as-received condition and agglomerates to larger stringers at very high temperatures (1400°C).<sup>4</sup> The constitution of these stringers is, at present, not known. Stringers seem to have no major effect on strength properties, transverse or longitudinal to the rolling direction. The most pronounced effect of the stringers appears to be on shearability. The sheared surfaces are irregular when shearing is done in the direction of the stringers (i.e. rolling direction) and are smooth and even when sheared in the transverse direction.

#### Hardness

The hardness of Zircaloy-2 follows the behavior of the tensile strength. Diamond pyramid hardness values (DPH) at room temperature for the four curves in



Fig. 1 are also tabulated on the figure and reflect, as expected, the strength level of the material tested. The values listed are based on a load of 30 kg. It should be remembered that even with a carefully prepared surface a very strong load dependence of DPH values is characteristic of zirconium and its alloys.<sup>2/</sup> This load dependence vanishes rapidly with increasing temperature; DPH values at room-temperature become load independent only above 25 kg, and at liquid nitrogen temperature DPH values continue to decrease up to the limit of the load capacity of the hardness tester. Another consideration in hardness testing is its orientation dependence. The hardness on planes parallel to the rolling plane may be as much as 20 DPH units above the hardness on transverse or longitudinal cross sections. The latter impressions have a rhombohedral shape, and the ratio of the diagonals is a convenient measure of the anisotropy which exists perpendicular to the rolling plane.

Hardness values as a function of temperature are shown by the dashed line in Fig. 1.<sup>5/</sup> The parallel trend of tensile strength and hot hardness is apparent and may be expected to continue to such temperatures for which no experimental values of tensile strength are available. (The Battelle report<sup>5/</sup> gives hot hardness data to 800°C). The logarithm of hardness (DPH) versus temperature plots as a sequence of two straight lines with a break at 550°C toward decreasing hardnesses.

#### DISCUSSION OF DUCTILITY

##### Uniform Elongation

Ductility of any metal is a more elusive property than strength, and Zircaloy-2 is no exception. A plot of three measures of ductility as a function of testing temperature is shown in Fig. 3. The curves are not as smooth as the strength curves in Fig. 1 and in most cases the variability of ductility measurements

is larger than that for the corresponding strength (See Table I). The three measures of ductility in Fig. 3 are uniform elongation, reduction in area from tensile test data, and impact energy of V-notch charpy bars. Of the three sets of curves, the one for uniform elongation shows the smoothest variation with temperature. Uniform elongation is very nearly equal to the work hardening exponent  $n$ ; because the natural strain ( $\delta$ ) at the maximum load (uniform strain) equals the work hardening exponent in a material which follows the power law  $\sigma = K\delta^n$ . This law is a good approximation of the plastic behavior of Zircaloy-2; i.e., when the true stress is plotted against the natural plastic strain on log-log paper the stress-strain curve becomes nearly a straight line. Increasing temperature and cold work decreases uniform elongation as well as the work hardening exponent (Fig. 3). In the 60% cold-rolled condition the uniform elongation remains constant above room temperature.

#### Reduction in Area

The reduction in area is a complex measure of ductility since it incorporates the uniform elongation as well as the heterogeneous (tri-axial) deformation beyond the point of instability, the so-called necking strain. Particularly in the latter stage the ductility is strongly influenced by microstructural discontinuities. From the curves in Fig. 3 it is apparent that the reduction in area is not a monotonously increasing function with temperature. Depending on the state of cold work the increase in ductility with temperature is interrupted between 150 and 350°C. This behavior is reminiscent of the blue-brittle range in the low and medium carbon steels. The attenuation of ductility at these elevated temperatures is more pronounced in the transverse direction. Transverse specimens with more than 25% cold work exhibit a decrease of reduction in area with increasing temperature between 150 and 350°C. The ductility subse-

quently rises sharply at about  $400^{\circ}\text{C}$ . The reason for this deficiency in ductility at elevated temperatures is not known, though hydrogen is a suspected cause. The usual concentration of 40 to 50 ppm can be taken into solution at about  $400^{\circ}\text{C}$  which would explain the good ductility above this temperature, since hydrogen in solution is known to have no detrimental effect on ductility. On the other hand, it has been shown that in zirconium small amounts of hydrogen in the form of hydrides can greatly reduce the necking strain<sup>6/</sup> and a similar effect is expected in Zircaloy-2. Fig. 4 shows a longitudinal section through the fractured end of a round tensile specimen containing 45 ppm of hydrogen tested at room temperature. Note the porosity which develops in the necked region presumably because of hydride precipitation and tri-axial strain. Also note the absence of a typical cup-cone failure of this "ductile" material. It is believed that the ductility of Zircaloy-2 can be increased by inhibiting the initiation of pores or in other words by preventing the precipitation of hydride. In this connection it is well to keep in mind the tendency of Zircaloy-2 to pick up hydrogen in corrosive media which is discussed in detail further on.

#### Ductility in Impact

Another striking measure of the effectiveness of small amounts of hydrogen is its pronounced effect on the impact strength.<sup>7,8/</sup> The two impact energy curves show the typical transition temperature behavior of Zircaloy-2.<sup>3/</sup> Let the 10 ft-lb level be an arbitrary definition of the transition temperature. It is seen that the beta-quenched condition ( $1010^{\circ}\text{C}$ -1 hr-He-water quenched) has a transition temperature of  $-50^{\circ}\text{C}$ , while in the same condition an aging treatment ( $400^{\circ}\text{C}$ -3 hrs-furnace cool) increases the transition temperature nearly by  $200^{\circ}\text{C}$ . Mudge<sup>7/</sup> has shown that this increase in transition temperature is associated with a metallographically observable formation of hydride. The hydrogen content

pertaining to the impact curves in Fig. 3 is 40 ppm. Increasing the hydrogen content of Zircaloy-2 to 410 ppm shifts the transition temperature to nearly 300 °C.<sup>8/</sup>

It would be an error to conclude from the results of impact tests alone that the beta-quenched condition is beneficial with regards to ductility. Other effects will have to be considered; one of which is that beta grain growth will occur when Zircaloy-2 is held in the beta region (roughly above 1000°C). When these large grains are quenched into the alpha region the diffusionless transformation from body-centered cubic beta to close-packed hexagonal alpha results in many alpha grains of related orientation within each parent beta grain. The mechanical response of such a system is that the related alpha grains act as a unit as though the prior-beta grain were present, and thus separation along prior-beta grain boundaries during deformation is quite common. Whether this separation is due to impurity effects in the prior-beta grain boundaries or due to differences in slip mechanism in adjacent prior-beta grains (because of family relations among the alpha grains) is not known. The separation along prior beta-grain boundaries has also been encountered upon welding in conjunction with shrinkage stresses.

#### C. CORROSION PROPERTIES

The most important single property of Zircaloy-2 is its excellent corrosion resistance in high temperature water in which respect it is vastly superior to unalloyed zirconium. The corrosion behavior of unalloyed zirconium as well as the details of corrosion testing techniques is described in the literature.<sup>9,10/</sup> The corrosion of unalloyed zirconium in high temperature water is characterized by the formation of a tightly adherent zirconium dioxide film during a more or less protracted period of exposure after which the oxide

becomes non-adherent. During the first period a quasi-cubic rate law is followed, while in the second period a linear rate law is followed. The time at which the first period is interrupted is highly variable and is shortened when small amounts of nitrogen or other impurities are present in the metal. Further, the corrosion rate during the second period is very high. In the case of Zircaloy-2, however, the time at which the initial period is interrupted is highly reproducible, and is relatively insensitive to impurity content, and in the second period the corrosion product is adherent and the corrosion rate is low. These are the principal advantages of Zircaloy-2 and they become more pronounced with increasing temperature. A further advantage which is derived from the decreased sensitivity to impurity content is that Kroll process sponge zirconium can be utilized in Zircaloy-2.

#### Kinetics

The kinetics of the corrosion of Zircaloy-2 in high temperature water are shown in Fig. 5. Since the corrosion produced oxide remains on the surface, the increase in weight of the specimen is a measure of the amount of corrosion. Thus, in Figure 5, the weight gain is plotted as a function of time on logarithmic scales for exposure in 550, 600 and 680°F water. During the initial period the corrosion kinetics may be represented by the empirical equation:

$$\Delta m = kt^n \quad (1)$$

where  $\Delta m$  is the weight gain  
 $t$  is the exposure time  
 $k$  and  $n$  are constants, dependent on temperatures.

The change from the initial kinetics to the final kinetics has been termed "transition". The post-transition corrosion kinetics are described by a simple linear equation relating weight gain and exposure time. It will be noted that a transition is not shown for exposures at 550 and 600°F since experimental data for very long exposures are not available. However, the time required for transition

can be estimated by assuming that transition occurs at the same weight gain at 600°F as it does at 680°F, and the post-transition corrosion rate at 600°F can be estimated by a technique involving pre-exposure at a higher temperature.<sup>11/</sup> The kinetics data are summarized in Table II in which the logarithmic form of Equation 1 is employed.

Table II

Empirical Equations for the Corrosion Behavior of Zircaloy-2

Temperature °F	°C	Pressure psi	Equation $\Delta m$ in mg/dm <sup>2</sup> , t in days
550	288	750	$\log \Delta m = 0.50 + 0.30 \log t$
600	316	1553	$\log \Delta m = 0.74 + 0.26 \log t$ Up to 1150 days ( $\Delta m-34$ ) = 0.065 (t-1150) *After 1150 days
680	360	2705	$\log \Delta m = 0.76 + 0.38 \log t$ Up to 112 days ( $\Delta m-34$ ) = 0.37 (t-112) After 112 days
750	400	1500	$\log \Delta m = 1.10 + 0.32 \log t$ Up to 41 days ( $\Delta m-41$ ) = 1.27 (t-41) After 41 days

\* Estimated

Included in Figure 5 and Table II are data pertaining to the exposure of Zircaloy-2 to superheated steam at 750°F and 1500 psi. Under these conditions Zircaloy-2 appears to follow the same type of kinetics as it does in water at lower temperatures. This is further substantiated by the fact that curves relating corrosion to composition have the same features whether exposure is in steam or in water. Such a steam test has been employed extensively as an accelerated test, and frequent reference will be made to the results of such tests in this paper.

The Effect of Composition

The corrosion properties of Zircaloy-2 are not sufficiently sensitive to composition so that reasonable variations about the nominal composition need not be of concern in the practical sense. The effect of tin content, when the

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iron, nickel and chromium content are held constant, upon corrosion resistance in 680°F water is slight as may be seen in Figure 6. Since one of the functions of tin in Zircaloy-2 is to counteract the deleterious effect of nitrogen,<sup>10/</sup> the shape of curves such as are shown in Figure 6 depend upon the nitrogen content of the metal. The curves shown are for alloys containing 60 to 90 ppm of nitrogen. Higher nitrogen contents would cause the corrosion resistance to decrease with decreasing tin content. At higher temperatures in steam the corrosion rate increases with increasing tin content.

The effect of the addition of iron, nickel, or chromium upon the corrosion behavior of zirconium-tin base alloys has been reported.<sup>10/</sup> In the case of alloys containing iron or nickel, maximum corrosion resistance occurs at about 0.25 w/o, while chromium appears to be less effective. Attempts to determine the individual effects of iron, nickel, and chromium in normal Zircaloy-2 have failed to show any marked dependence. However, the data suggest that corrosion resistance passes through a maximum as the combined iron, nickel, and chromium content increases. This effect is suggested in Figure 7 where the total range of combined alloying elements is somewhat greater than the specified range.

On the basis of work done on Zircaloy-2 and other zirconium-base alloys the functions of the alloying elements may be discussed.<sup>10/</sup> The function of tin in Zircaloy-2 is to overcome the deleterious effect of impurities which may be in the sponge feed stock, and to promote the adherence of the corrosion product. The reasons for the latter function are not understood. However, the action of tin in counteracting the harmful effect of nitrogen is believed to be due to the clustering of  $\text{Sn}^{+3}$  ions,  $\text{N}^{-3}$  ions and vacant  $\text{O}^-$  sites in the oxide lattice, thus tending to prevent  $\text{O}^-$  vacancies, formed as a result of the presence of  $\text{N}^{+3}$ , from

participating in the transport of  $O^{2-}$  through the oxide. Iron, nickel, and chromium are believed to be interchangeable in their functions in Zircaloy-2, although it is evident that chromium is less effective than the other two. These elements appear also to tend to counteract the effect of nitrogen. In this respect these elements may act through a mechanism such as that mentioned for tin. These elements also contribute to adherence of the oxide. Unlike tin or any other known alloying elements, iron and nickel, and to a lesser extent chromium, improve the corrosion resistance of zirconium apart from effects involving impurity elements. This effect is believed to be associated with the corrosion product, hydrogen, to be discussed below. It is believed that the hydrogen picked up by the zirconium during corrosion may play a role in corrosion failure. In the case of Zircaloy-2 it is believed that iron and nickel and possibly chromium promote the recombination of nascent hydrogen, produced at the surface by the corrosion reaction, and thus limit the amount of hydrogen picked up by the metal.

The effect of nitrogen content upon the weight gain after various exposure times in 750°F steam is shown in Figure 8. It will be noted that the deleterious effect of nitrogen becomes evident at lower nitrogen concentration as the exposure time increases. Thus, the amount of nitrogen which can be tolerated will depend upon the severity of the particular application. After 140 days in 750°F steam the effect of nitrogen does not appear to set in until nitrogen content is raised to about 100 ppm.

The effect of oxygen upon the corrosion properties of Zircaloy-2 is absent or very small in the range 400 to 2000 ppm. The effect of other impurities such as aluminum, lead, silicon, copper, and manganese is harmful when these elements are present in quantities somewhat greater than those



indicated in Part A.<sup>12/</sup> However, precise data are not available.

#### Effect of Heat Treatment

The effect of annealing at various temperatures from 500 to 1000°C followed by either quenching or furnace cooling upon corrosion properties is shown in Figure 9. It is to be noted that annealing at 900 or 1000°C results in somewhat higher corrosion rates in 680°F water or 750°F steam than is the case for annealing at lower temperatures. The corrosion properties are not particularly affected by cooling rate.

#### Hydrogen Pickup and Effect of Hydrogen Content

Experiments in which the hydrogen content of thin foil specimens has been determined as a function of exposure time in hot water show that hydrogen is picked up during corrosion.<sup>10,13,14/</sup> The source of hydrogen is presumed to be that evolved by the metal-water reaction since the amount of hydrogen picked up is proportional to the amount of corrosion. Zircaloy-2 picks up about 10 to 20% of the hydrogen evolved in the corrosion reaction in 750°F steam and about 5 to 15% of that at 680°F. Unalloyed sponge was found to pick up about 30% of the corrosion product hydrogen. The addition of hydrogen to the test water (2000 cc/liter) results in the pickup of up to thirteen times the pickup in degassed water with no effect upon the corrosion rate.

Current, incomplete data for specimens in which the initial hydrogen content varies from 4 to 10,000 ppm indicate that the corrosion rate increases gradually with increasing hydrogen content, the total weight gain of the specimens with 10,000 ppm H<sub>2</sub> after 42 days in 750°F steam being only about three times that for specimens containing 4 ppm of hydrogen.

The insensitivity of corrosion rates to hydrogen content suggest that hydrogen may not play an important role in the corrosion mechanism of Zircaloy-2.

This is further substantiated by the fact that the kinetics of the oxidation of Zircaloy-2 exposed in pure, dry oxygen are identical to those of its corrosion in steam at the same temperature.<sup>14/</sup>

#### Application of Corrosion Data

The limitation imposed by corrosion properties upon the use of Zircaloy-2 does not arise from consideration of the loss of metal and consequent mechanical failure. This is evidenced by the post-transition rates shown in Table I which range from 0.065 to 1.27 mg/dm<sup>2</sup>/day at 600 to 750°F. In terms of metal corroded these rates correspond to 0.4 to 7 x 10<sup>-4</sup> inches per year.

It is under conditions of heat flux through the surface that the corrosion properties of Zircaloy-2 become limiting in nuclear reactor application. In the case of a Zircaloy-2 clad fuel element there are three temperatures with which one is concerned. These are the surface temperature, the temperature at the metal/oxide interface and the maximum temperature of the fuel material within the fuel element. Under conditions of constant heat flux and constant surface temperature it is evident that the temperature at the metal/oxide interface increases as the oxide thickness increases due to corrosion, since zirconium dioxide has a very low thermal conductivity. The fact that the corrosion rate after transition is linear suggests that the reaction rate is limited by diffusion through a thin layer of oxide next to the metal and that the remainder of the oxide is relatively pervious. Thus, under heat throughput conditions the corrosion rate will increase as the oxide thickens. This effect is not pronounced until transition has been reached.

As corrosion proceeds and the oxide thickens under heat throughput conditions the corrosion rate increases and the maximum fuel temperature rises in a way which can be calculated.<sup>15/</sup> The extent of corrosion then is considered excessive when the fuel element cladding is breached or when the fuel temperature

becomes too high. Which of these occurs first depends upon the particular geometry of the fuel element, the nature of the fuel material, the surface temperature and the heat flux.

#### CONCLUSIONS

The mechanical and corrosion properties of Zircaloy-2 were reviewed and the following general conclusions drawn:

1. Tensile strength, yield strength, and hardness decrease regularly with increasing temperature in the range from -200 to 500°C. Only small differences were found between longitudinal and transverse strength properties in the as-received as well as in the cold rolled condition.

2. Ductility as measured by uniform elongation decreases regularly with temperature. Ductility as measured by reduction in area increases with temperature and reaches a plateau in the range from 150 to 350°C. With increased amounts of prior cold work the reduction in area actually decreases with temperature in the range from 150 to 350°C.

3. Ductility as indicated by impact energy encounters a transition temperature at about -50°C. The transition temperature is raised by increasing hydrogen content or by heat treatments which precipitate hydride.

4. Zircaloy-2 corrodes in high temperature water at very low rates. Corrosion kinetics are initially quasi-cubic, and later become linear, the corrosion rate in the latter period being greater than at the end of the former period.

5. The functions of the alloying elements with respect to corrosion properties are discussed. Nitrogen in excess of 60-100 ppm in the metal has a deleterious effect upon the corrosion properties of Zircaloy-2.

6. In general, metal attrition by corrosion is not a problem in

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itself. Rather the acceleration of corrosion and the temperature rise within a fuel element accompanying the transfer of heat through the corrosion product dictates the permissible corrosion rate or limits the useful lifetime.

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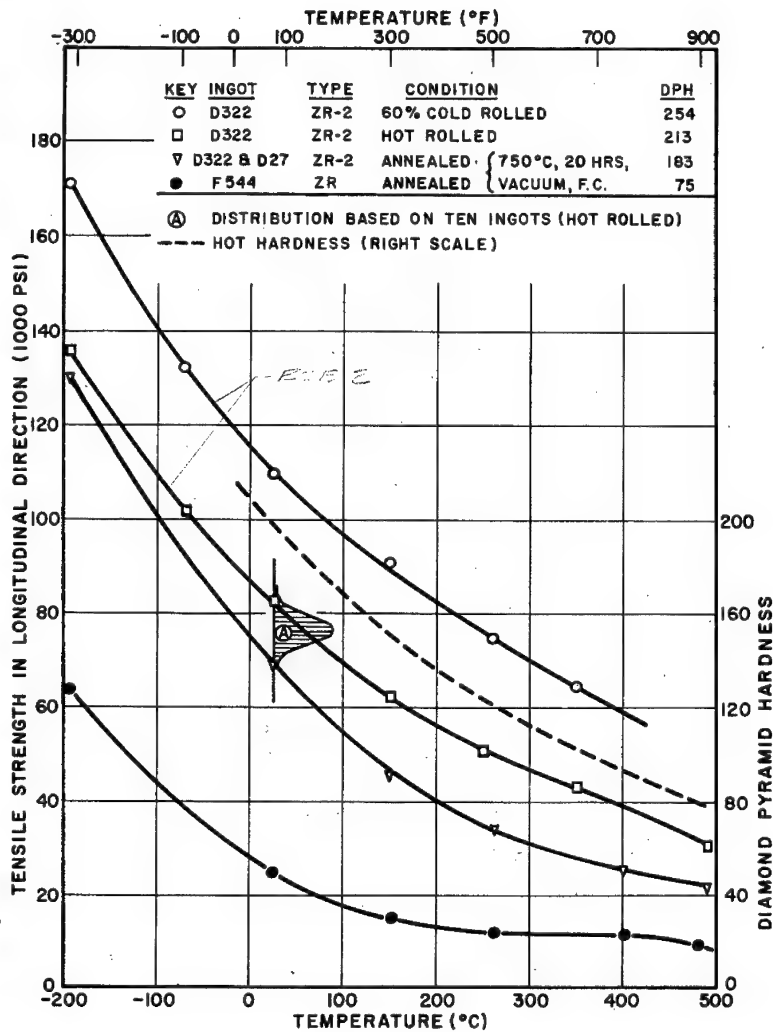
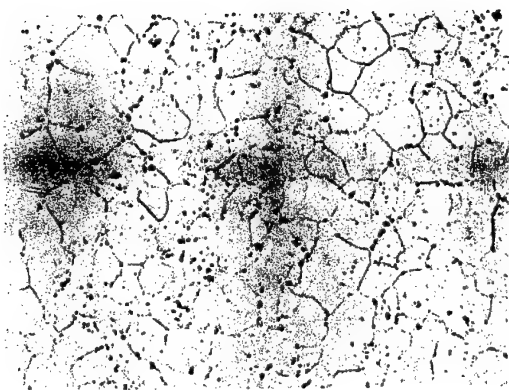
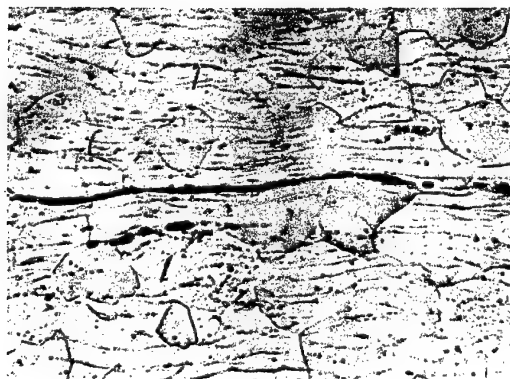


Fig. 1  
Effect of Temperature on the Strength and  
Hardness of Zircaloy-2

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a. Transverse cross section.



b. Longitudinal cross section.

Fig. 2 - Microstructure of Base-annealed Zircaloy-2 (400X)

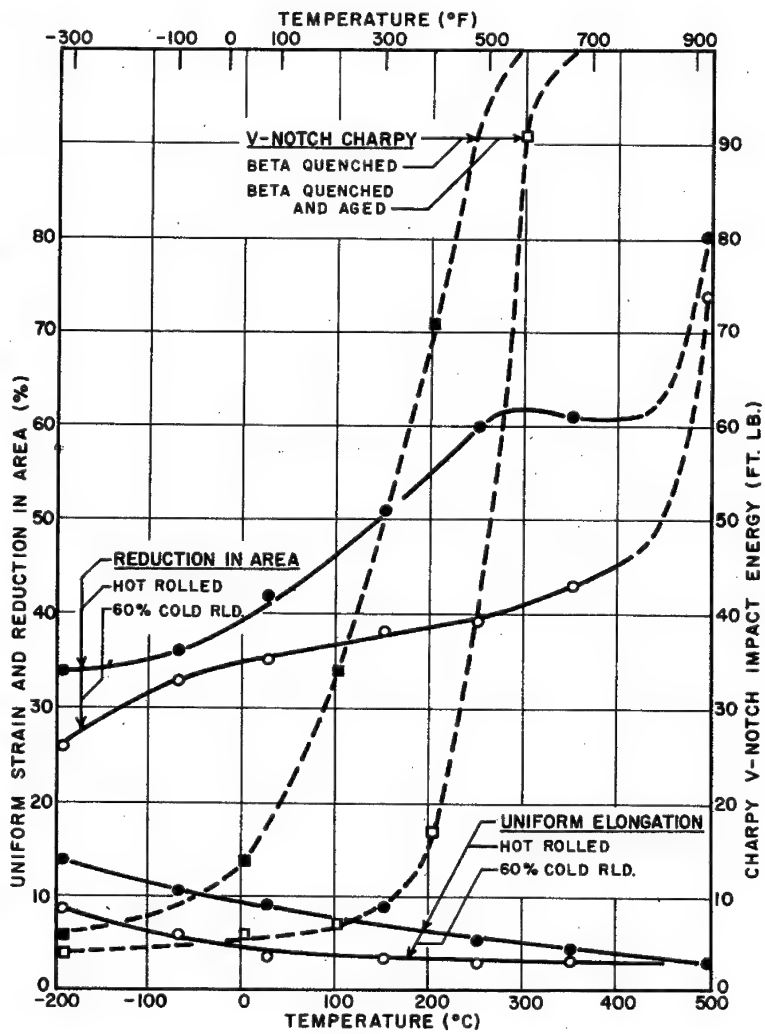


Fig. 3 - Effect of Temperature on the Ductility and Impact Strength of Zircaloy-2



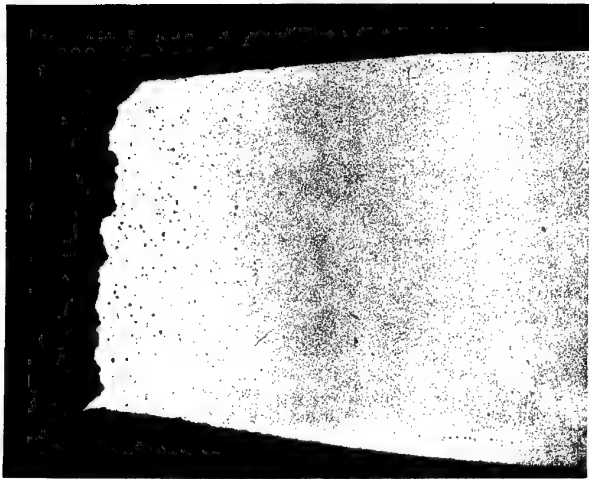


Fig. 4 - Appearance of Strain Induced Porosity  
Near Fractured End of a Round Zircaloy-2  
Tensile Specimens (45 ppm hydrogen).  
Magnification 13X.

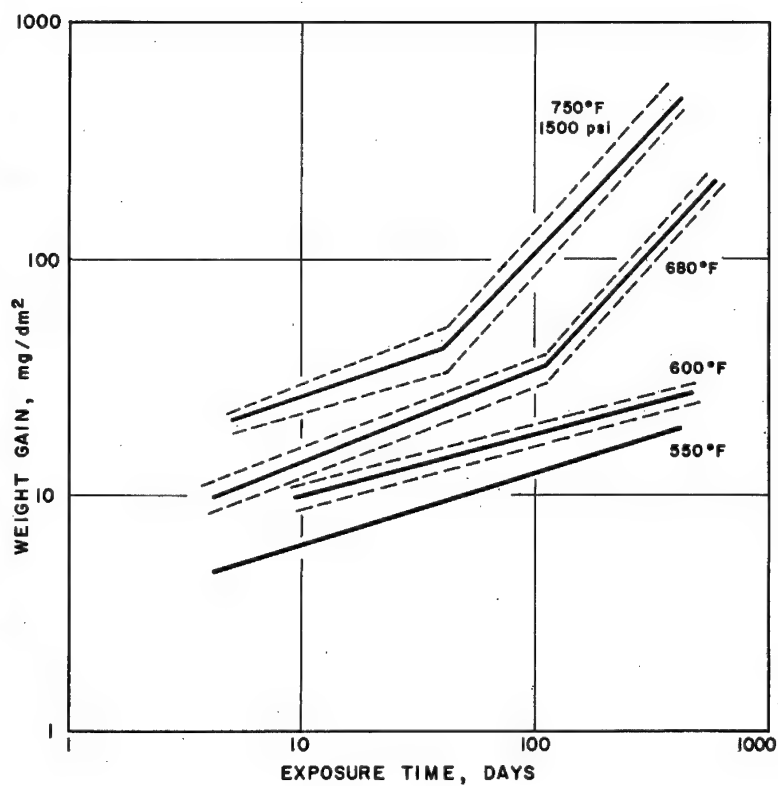


Fig. 5 - Weight Gain-Time Curves for Zircaloy-2 Exposed to High Temperature Water and Steam. The specimens exposed at 550, 680 and 750°F were previously annealed below 800°C. The specimens exposed at 600°F were exposed in the hot-rolled condition.

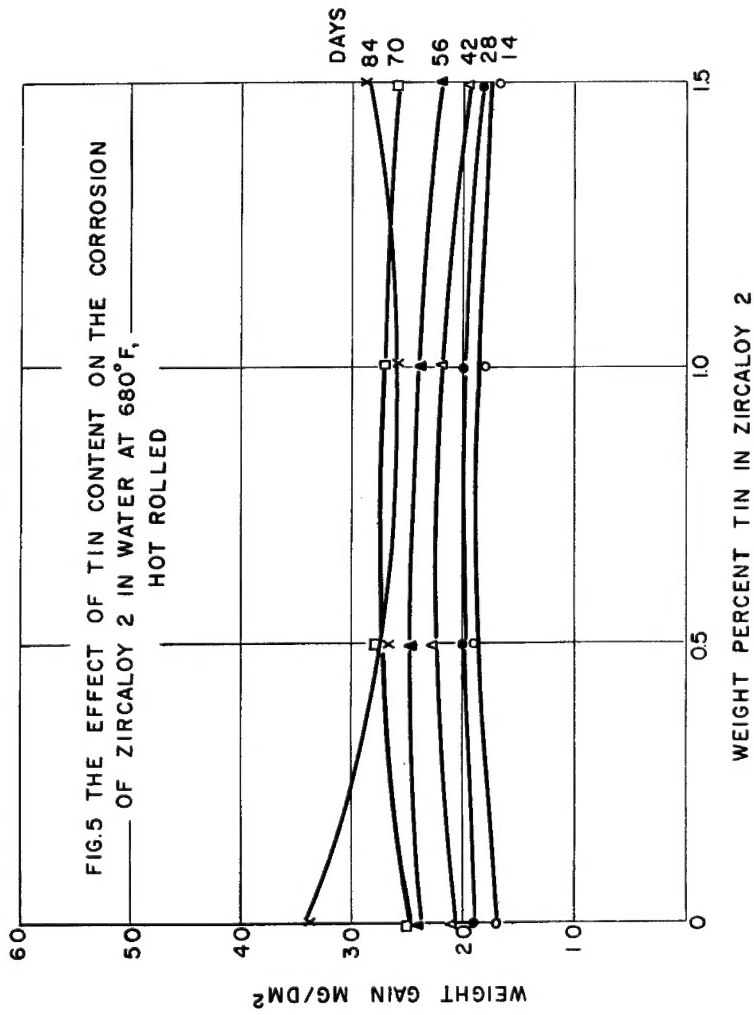


Fig. 6

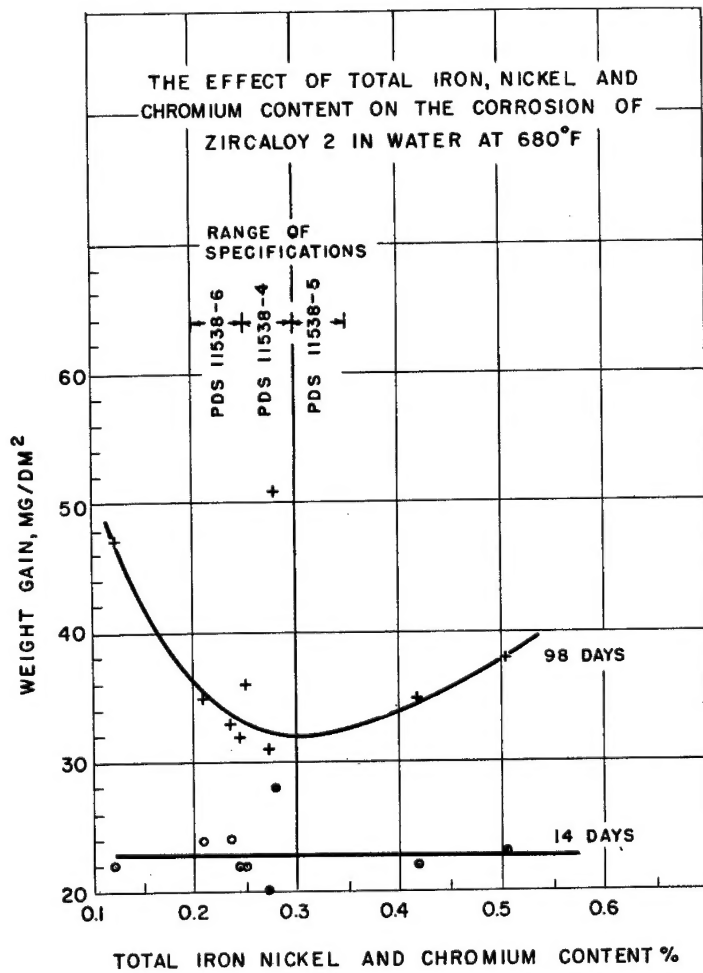


Fig. 7

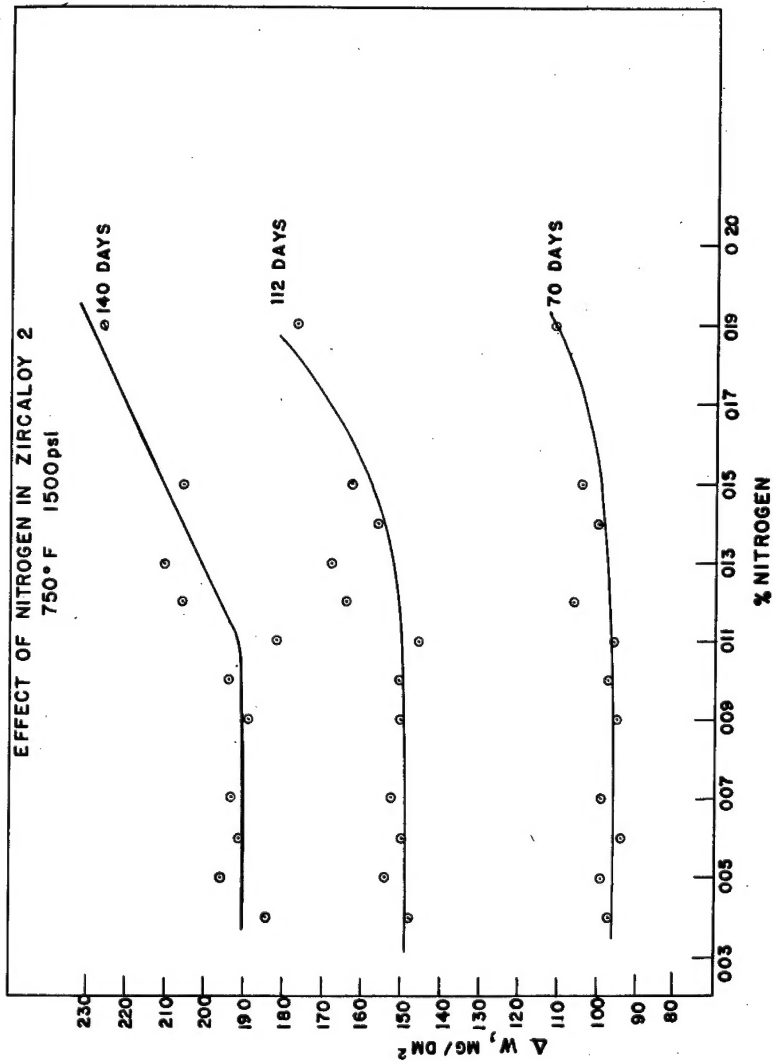


Fig. 8

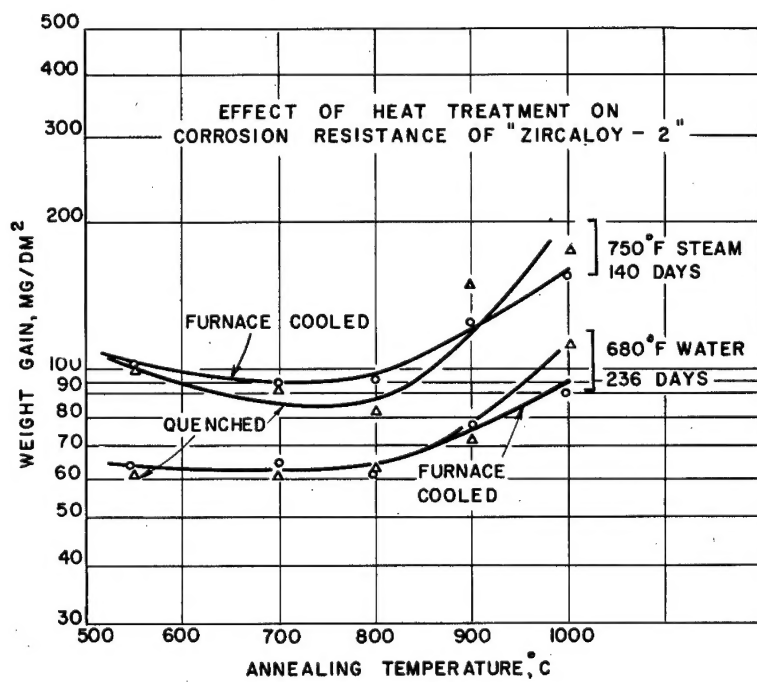


Fig. 9